host foraging behavior of *Aphidius ervi*. *J. Chem. Ecol.*, **22** (1996) 1591–605.
4. Turlings, T. C. J., Tumlinson, J. H., Eller, F. J. & Lewis, W. J., Exploitation of herbivore-induced plant odors by host-seeking parasitic wasps. *Science* (Washington), **250** (1990) 1251-3.
5. Takabayashi, J., Dicke, M. & Posthumus, M. A., Variation in composition of predator-attracting allelochemicals emitted by herbivore-infested plants: relative influence of plant and herbivore. *Chemoecol.*, **2** (1991) 1–6.
6. Hardie, J., Nottingham, S. F., Powell, W. & Wadhams, L. J., Synthetic aphid sex pheromone lures female parasitoids. *Entomol. Exper. Appl.*, **61** (1991) 97–9.
7. Powell, W., Hardie, J., Hick, A. J., Höller, C., Mann, J., Merritt, L., Nottingham, S. F., Wadhams, L. J., Witthinrich, J. & Wright, A. F., Responses of the parasitoid *Praon volucre* (Hymenoptera: Braconidae) to aphid sex pheromone lures in cereal fields in autumn: Implications for parasitoid manipulation. *Eur. J. Entomol.*, **90** (1993) 435–8.
8. Wratten, S. D., & Powell, W., Cereal aphids and their natural enemies. In *The Ecology of Temperate Cereal Fields*, ed. L. G. Firbank, N. Carter, J. F. Darbyshire & G. R. Potts. 32nd Symposium of the British Ecological Society. Blackwell, Oxford, 1991, pp. 233–57.

The Commercial Exploitation of Pheromones and other Semiochemicals

Owen T. Jones

AgriSense BCS Ltd, Treforest Industrial Estate, Pontypridd, Mid Glamorgan, CF37 5SU, UK

Introduction

It is now almost 40 years since the first insect pheromone was isolated and identified and many authors have referred over the years to their commercial potential. Much progress has been made during those years in terms of scientic and technological advances related to semiochemicals and in our understanding of pest behavioural ecology,[1,2] but few authors have questioned the 'progress' that has actually been made in terms of the commercial exploitation of pheromones and other semiochemicals; this paper reviews the extent to which the potential of these substances has been translated into commercial reality.

The semiochemical industry today

Based on published data and unpublished information which has been made available to the author, semiochemical-based products are estimated to have world-wide sales in the US$ 70–80 million range at the manufacturers' level. This compares with a world-wide insecticide market of nearly US$ 8 billion in 1995[3] so that it therefore constitutes less than 1% of that market. In terms of the biopesticide market (bacteria, viruses, botanical insecticides, entomopathogenic nematodes and beneficial insects) on the other hand, semiochemicals constitute a much higher percentage (*c.* 30%) and probably are third in importance after bacterial and botanical products.[4] The industry has taken over 20 years to achieve its current size and this growth has been pioneered mostly by small to medium-sized enterprises (SMEs).

Semiochemical-based products have found markets all over the world, with no great concentration on any one continent. The producers of these products, however, are concentrated in the USA, Europe and Japan, and over 60% of the sales are achieved by about a dozen companies. The sale of traps and lures for monitoring insect pests accounts for nearly 40% of the semiochemical market, while the bulk of the remaining sales comes from mating disruption products for moth pests. Table 1 shows the geographic spread of the market by sales and pest species together with the names of the principal companies involved in the industry.

Semiochemical-based products for insect pest monitoring

Pheromone-based monitoring systems provide one of the most reliable and effective survey methods for pest detection and quantification.[5,6] They have been used extensively in quarantine pest detection and in detecting movement of pest species into a crop. There have been difficulties in their use for quantitative measurements of insect populations but their role in optimising the timing of insecticide applications is growing in popularity and has led to substantial reductions in pesticide use. Although the market expectations for semiochemical-based products in insect monitoring were never very great, an estimate of their current global sales for this purpose at the manufacturers' level comes to about US$ 27 million. In many cases the market had to be generated from an almost non-existent base. These products have found their way into most situations where insects are a problem, including the major world crops cotton, rice, vegetables, fruit, forestry and protected horticultural crops, and also where pests attack food and fibre during their manufacture, storage and distribution. The regulatory hurdles for these products are not very significant given that they are used for 'monitoring' pests and not for 'controlling', 'suppressing' or in any way 'mitigating' their numbers. Such intentions for a product would immediately subject it to the regulatory processes relating to that intended use.

Monitoring systems are best viewed as diagnostic kits in terms of their market potential, their purpose for use and their regulatory treatment.[7] The growth in the use of semiochemical-based monitoring traps has been substantial over the last two decades and will continue in the future, given the ever-increasing concerns about pesticide residues in food, the need to reduce pesticide usage, and the food industry's preoccupation with risk

TABLE 1

Estimates for the World Market at Producers' Prices for Semiochemical-Based products used both in Monitoring and Control of Insect Pests.

Region	*Use*	*Target crops and species*	*Estimated market US$ million*	*Active Companies (majority sell both monitoring and control products)*
North America (Canada, Mexico and USA)	Monitoring	Medfly, boll weevil, gypsy moth, fruit pests	10	Consep Inc, Ecogen Inc, Pacific Biocontrol Inc, Thermo Trilogy Inc, Troy Biosciences Inc, Trécé Inc,
	Control	Codling and other fruit tree moths, pink bollworm, bark beetles, tomato pinworm houseflies	16	Hercon Environmental , Phero Tech Inc, Insects Limited Inc.
Europe, North Africa, Middle East	Monitoring	Pink bollworm and other cotton pests, vine, top fruit and stored product pests	10	Agrisense BCS Ltd, BASF AG, Cyanamid Agrar GmbH, Isagro SpA, International Pheromone Systems Ltd, Oecos Ltd, Russell Environmental
	Control	Pink bollworm, grape pests, fruit tree moth pests, bark beetles, houseflies	18	Products Ltd, Trifolio-M GmbH. Vioryl, S.A.
Far East and the Rest of the world (S. America, S. Africa, Australia	Monitoring	Fruit flies, cotton pests, vegetable and top-fruit pests, plantation pests	7	Shin-Etsu Chemical Co. Ltd, Chem Tica Internacional S.A., Consep Inc, Ecogen Inc, Troy Biosciences Inc, Trécé Inc, Hercon Environmental,
and NZ)	Control	Fruit flies, top-fruit pests especially codling moth, cotton pests, tea pests houseflies	13	Insects Limited Inc, AgriSense BCS Ltd, I.P.S. Ltd, Oecos, Russell Environmental Products Ltd, Trifolio-M GmbH

management and the need for due dilligence and traceability where it concerns pesticide use on food. The way in which data from monitoring are collected, handled and interpreted may become more complex at a scientific level, but it is likely to become more user-friendly.[8]

Semiochemical-based products for controlling insect pests
Whereas the market expectations for the insect-monitoring products based on semiochemicals were never very great, those for control products based on semiochemicals were always projected, especially in the 1970s and 1980s, to be large.[9] Several strategies were proposed for these substances including mass trapping, lure and kill and mating disruption. The possibility of mass trapping using pheromones was always limited, since the majority of the pheromones described were from lepidoptera where their primary function was in attracting males. In addition, the trapping efficiency of many trap designs is often very low, making it impossible to catch sufficient numbers of males to leave females unfertilized. Successful mass trapping has been achieved where pest populations have been low and where the attractant used has been effective on both sexes.[10] The inefficiencies of trap catch can be overcome by using a conventional insecticide as a killing agent instead of a physical device in the form of a trap. The semiochemical lures the insect to an area where it is killed with an appropriate adulticide. Again the technique is limited if male-attracting pheromones are used. There are a number of successful products which are based on this technique, and a lure-and-kill insecticide granular formulation which carries the sex pheromone of the common housefly (*Musca domestica* L.) is a case in point. The pheromone attracts both sexes and induces greater arrestment of the flies on the insecticide granules, thus improving their efficiency substantially.[11] With the identification of other non-pheromonal attractants such as host-plant chemicals and oviposition stimuli, for example, the scope for controlling insect pests using female attract-and-kill formulations and devices becomes much greater, and future developments are expected in this area.

Most of the efforts made in using semiochemicals for controlling insect pests over the last two decades have been in the field of mating disruption using sex pheromones of lepidopteran pests. Many small start-up companies entered the market with great expectations but have found the task of selling such products much more difficult than was initially thought. Many of those early pioneers have failed, withdrawn from the market or have been sold to other bio-pesticide companies. Those that are active in this market today have had to develop strategies which give the best chance of success given the limitations of the technology, while at the same time allowing for the relatively slow development of the market. We estimate the current market for mating disruption products at the manufacturers' level to be about US$ 25 million, with the pink bollworm (*Pectinophora*

gossypiella (Saunders)), the codling moth *Laspeyresia pomonella* (L.) and various grape moth pests being amongst the most important species where the technique has been shown to work successfully on a commercial scale. Indeed, over 500,000 acres of cotton has been treated annually over the last four years in Egypt with mating disruption formulations for the pink bollworm, maintaining satisfactory levels of control during the whole of that time.

Three factors have been paramount in determining the rate of development of the mating disruption market using pheromones:

(*1*) *The reliability and robustness of the technology*. In the case of this first factor, it has to be acknowledged that much progress has been made in terms of synthesis and consistency of supply of the pheromone active ingredients.[12] Similarly, in the case of controlled-release technology, much progress has been made with the advent of hand-applied dispensers such as 'Selibate' PBW or 'PB-Rope' for the pink bollworm.[13,14] Such dispensers made a significant contribution to the advancement of the technology in the early 1990s and a number of very successful area-wide programmes have resulted in places such as Egypt (cotton), the USA (apples) and Europe (vines). However, in many cases, the level of control achieved has not been acceptable at high pest population densities. The techniques can also be difficult to apply in small plots because of the problems caused by immigration of gravid females into the treatment areas. These are fundamental biological weaknesses in the system and will always be difficult to resolve no matter how good our understanding of the mechanisms by which mating disruption is achieved in the field. The latter is a matter of much debate and a clear picture of the underlying mechanisms in any particular pest species has been difficult to obtain.[15]

(2) *The cost effectiveness of the products*. As the amount of pheromones used has increased over the years the cost of manufacturing technical grade pheromone components has come down. In a few cases the costs of manufacture and formulation are now comparable to those of some conventional insecticides. The costs of application are relatively low, especially in developing countries where local labour is comparatively inexpensive and where the need to use hard currency to hire foreign application equipment and services is eliminated through the use of such local labour. Achieving a price premium in the crop protected from pests using pheromone technology has also proved very difficult. A small price premium of about 5% is typical but substantial price premiums for insecticide-free produce has not been achieved in the majority of cases.

(3) *The regulatory requirements*. Registration requirements for pheromone-based mating disruption products vary considerably around the world with possibly the most enlightened attitude shown by the Environmental Protection Agency in the USA. The EPA regard this technology as 'biorational' and the data requirements follow a tiered system. Tier 1 tests require only a limited number of acute studies and if the results from these tests indicate no obvious area of concern then tests from Tiers 2 and 3 are usually waived.[16] Such a system is slowly developing in Europe, but pheromone-based products are not regarded as a separate category under the EC91/414 Crop Protection Directive and are consequently not registered as expeditiously as in the USA. The costs of registration of such products, although generally less than for conventional pesticides in most countries, are still much higher as a percentage of their market potential than the equivalent for conventional pesticides (25% of market potential versus 1% for coventional pesticides according to the International Biocontrol Manufacturers Association).

Future prospects

Little progress is foreseen with the mass-trapping techniques until a much greater level of efficiency is achieved with the attractant lures and trap designs. Powerful attractants for the females are essential while trapping efficiencies of at least 90% are required in order to have the required impact on the pest population.

As far as 'lure-and-kill' technologies are concerned, increased interest is foreseen in target devices where the killing agent is contained upon the surface of the device and makes no contact with the crop being protected. This technology has the potential to give season-long control with only one application early in the season and can be used right up until harvest. However, the need for strong female attractants is also a prerequisite and real advances can only be made when such materials are developed.

Attempts are currently under way to combine the attraction and repulsion effects of semiochemicals to form robust push-pull systems of pest management[17] (or stimulo-deterrent diversionary strategies as it has been termed by Miller and Cowles).[18] In essence, semiochemicals are used to divert insect pests from the crop being protected to other parts of the crop, or even to non-host plants where they can be destroyed using conventional or biological insecticides. Early indications are that the sum of the two effects is not just additive but even synergistic. This is a very promising line of research which holds great potential for the future of semiochemicals.

The scope for applying mating disruption is limited; it is confined to lepidopteran moth pests which are not very dispersive and works best in area-wide treatments. Nevertheless we see a continued expansion in its use in niche markets where there are problems of insecticide resistance, lack of registered conventional products or

heightened environmental concerns in areas of special scientific interest or environmental conservation. There is a need for greater understanding of how the technique works in order to improve its efficiency. Publicly funded research support in this area would be highly desirable.[19]

References

1. Jutsum A. R. & Gordon, R. F. S. (eds), *Insect Pheromones in Plant Protection.* John Wiley & Sons Ltd., Chichester, 1989, 369 pp.
2. Ridgway, R. L., Silverstein, R. M. & Inscoe M. N. (eds), *Behaviour-Modifying Chemicals For Insect Management: Applications of Pheromones and Other Attractants.* Marcel Dekker Inc., New York, 1990, 761 pp.
3. Wood McKenzie Consultants Ltd, Agrochemical Monitor. Agricultural Biotechnology Report No. 120, 1995, Edinburgh, UK, 27pp.
4. Bio Science Securities, Inc., *The Outlook for Biopesticides.* In *Industry Report No. 1*, Orianda, California, 1996, 40 pp.
5. Wall, C. Monitoring and spray timing. In *Insect Pheromones in Plant Protection*, ed. A. R. Jutsum & R. F. S. Gordon. John Wiley & Sons Ltd, Chichester, 1989, pp. 39–66.
6. Wall, C., Principles of monitoring. *In Behavior-Modifying Chemicals For Insect Management: Applications of Pheromones and Other Attractants*, ed. R. L. Ridgway, R. M. Silverstein & M. N. Inscoe. Marcel Dekker Inc., New York, 1990, pp. 9–23.
7. Ridgway, R. L., Inscoe, M. & Arn, H. (eds), *Insect Pheromones and other Behaviour-Modifying Chemicals: Applications and Regulation. Proceedings of a Symposium held at the Brighton Crop Protection Conference—Pests and Diseases, 19 November, 1990* BCPC Monograph No 51, 1992, 135 pp.
8. Jones, O. T., The current and future prospects for semiochemicals in the integrated management of insect pests. *Proc. Brighton Crop Prot. Conference—Pests and Diseases*, (1994) 1213–22.
9. Shorey, H. H. & McKelvey, Jr, J. J., *Chemical Control of Insect Behaviour: Theory and Application.* John Wiley & Sons, Inc., New York, 414 pp.
10. Bakke, A. & Lie, R., Mass trapping. In *Insect Pheromones in Plant Protection*, ed. A. R. Jutsum & R. F. S. Gordon. John Wiley & Sons Ltd, Chichester, 1989, pp. 67–87.
11. Mitchell, E. R., Tingle, F. C. & Carlson, D. A., Effect of Muscalure on house fly traps of different color and location in poultry house, *J. Ga. Entomol. Soc.*, **10** (1975), 169–74.
12. Banasiak, D. S. & Byers, D. B., Olefin metathesis as an economical route to insect pheromones. In *Behaviour-Modifying Chemicals for Insect Management, Applications of Pheromones and Other Attractants*, ed. R. L. Ridgway, R. M. Silverstein & M. N. Inscoe. Marcel Dekker Inc., N. York, 1990, pp. 131–40.
13. Jones, O. T., Hall, D. R. & Smith, J. L., A new controlled release formulation which protects pheromones from isomerisation and degradation under field conditions. In *The use of pheromones and other semiochemicals in integrated control, ed.* H. Arn & R. Bues. Proceedings of a working group meeting held on 20–22 September 1988, Avignon, France IOBC-WPRS Bulletin XII (1989) pp. 151–2.
14. Kirsch, P. & Lingren, B., Commercial advancement on pheromone-related monitoring and control technology. *Proceedings of a working group meeting*, 11–14 May 1993, Chatham, UK. IOBC/WPRS Bulletin **16** (1993) 121–7.
15. Sanders, C. J., Mechanisms of mating disruption in moths. In *Insect Pheromone Research: New Directions*, ed. R. T. Cardé & A. K. Minks. Chapman & Hall, New York, 1997, pp. 333–346.
16. Lindsay, A. E., Insect behaviour-modifying chemicals: the status of current and proposed regulation in the United States. In *Insect Pheromones and other Behaviour-Modifying Chemicals: Applications and Regulations. Proceedings of a Symposium held at the Brighton Crop Protection Conference—Pests and Diseases, 19 November 1990*, ed. R. L. Ridgway, M. Inscoe & H. Arn. BCPC Monograph No 51, 1992, pp. 35–43.
17. Pyke, B., Rice, M., Sabine, B. & Zaluchi, M., The push-pull strategy—behavioural control of *Heliothis. Aust. Cotton Grower*, May-July 1987, 7–9.
18. Miller, J. R. & Cowles, R. S., Stimulo-deterrent diversion: a concept and its possible application to onion maggot control. *J. Chem. Ecol.*, **16** (1990) 3197–212.
19. Wyatt, T. D., Putting pheromones to work: paths forward for direct control. In *Insect Pheromone Research: New Directions*, ed. R. T. Cardé & A. K. Minks. Chapman & Hall, New York, 1997, pp. 445–59.

Semiochemicals: Foresight and Hindsight

J. R. Hillman

Scottish Crop Research Institute, Invergowrie, Dundee DD2 5DA, UK

Analysis of the potential market share of semiochemicals in integrated crop management is complex and must be seen in the light of other attractive areas of biological and crop science competing for resources. For example, the annual losses and costs of controlling late blight (*Phytophthora infestans* (Mont.) de Bary) of potato alone have been estimated by Centro Internacional de la Papa to be in the order of \$35–50 bn per annum. Around 15% of the world's agrochemicals are applied to cotton crops. Prophylactic nematicide usage across a wide range of fruit and vegetables, from pineapples to parsnips, is becoming a major concern worldwide. The value of UK potato industry for fresh and processed products approaches \$2 bn per annum.

Biological scientists are well aware of the inadequate appreciation by society generally of environmental costs, compounded by the fact that it is difficult to obtain even estimated costs to generate a case for investing in relevant R&D. Environmental accounting is still at a relatively primitive stage. Depressing as it may be, modern-day consumers have little (zero?) tolerance of pests and diseases on commodities; even parasitoids have the capacity to terrify shoppers in supermarkets. Low-cost produce coupled with a